Homestake based very large neutrino detector

Milind Diwan
Brookhaven National Laboratory

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Office of Science
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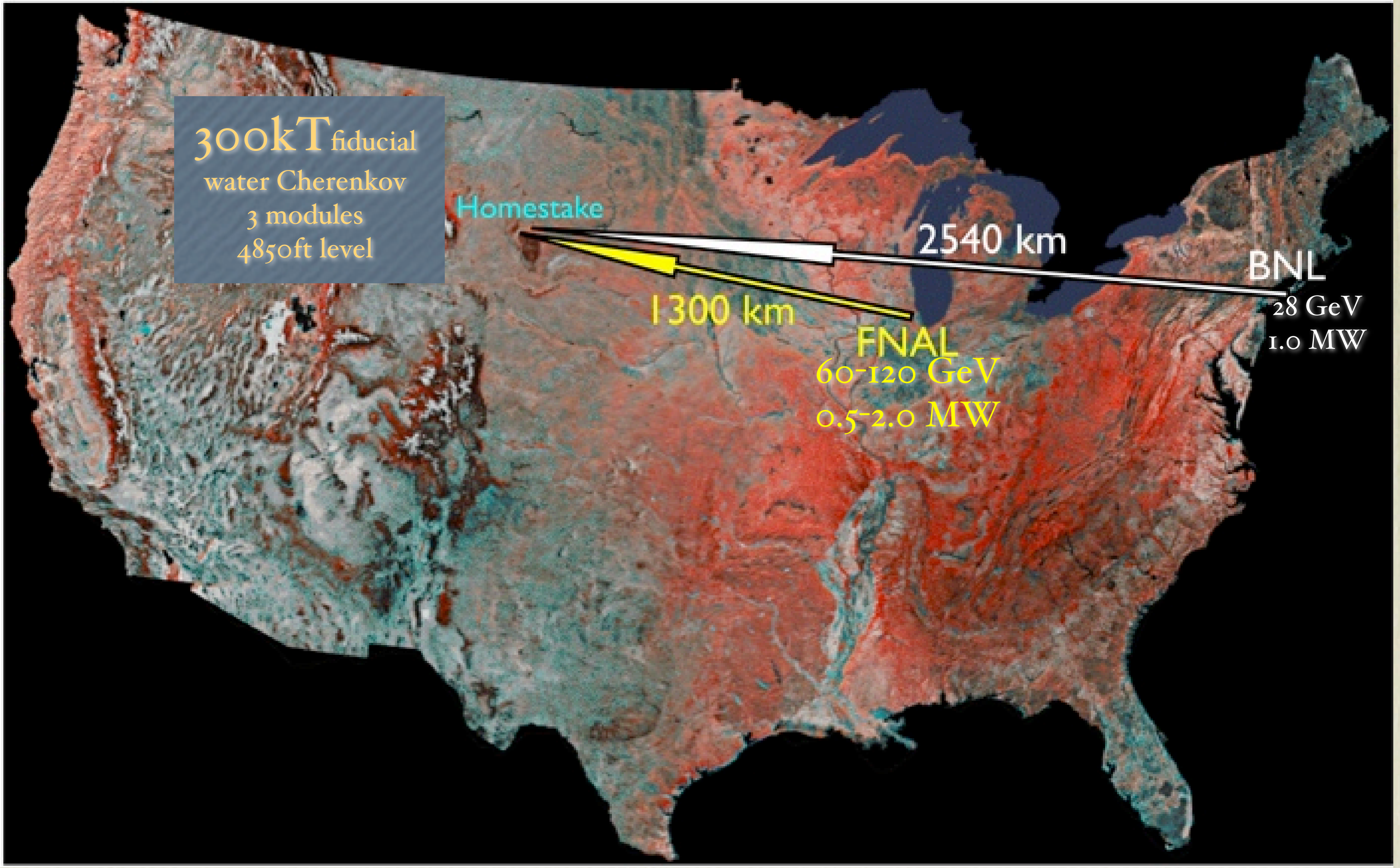
The concept originated ~2002 after SuperK and Kamland discoveries.



Key ideas

- Large statistics (>100k events per yr) with high energy muon neutrino beam.
- Large distance to get big matter and CP effects. Distance large enough to get both "atmospheric" and "solar" oscillation effects in single experiment.
- Broad scientific program for detector with low background and large dynamic range in energy.

Phenomenology of $\nu_\mu \to \nu_e$

The Mixing Matrix

$$
\begin{array}{ccccccc}
 & \text{Atmospheric} & & \text{Cross-Mixing} & & \text{Solar} \\
U = & \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} & \times & \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} & \times & \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}
\end{array}
$$

$c_{ij} \equiv \cos\theta_{ij}$
$s_{ij} \equiv \sin\theta_{ij}$

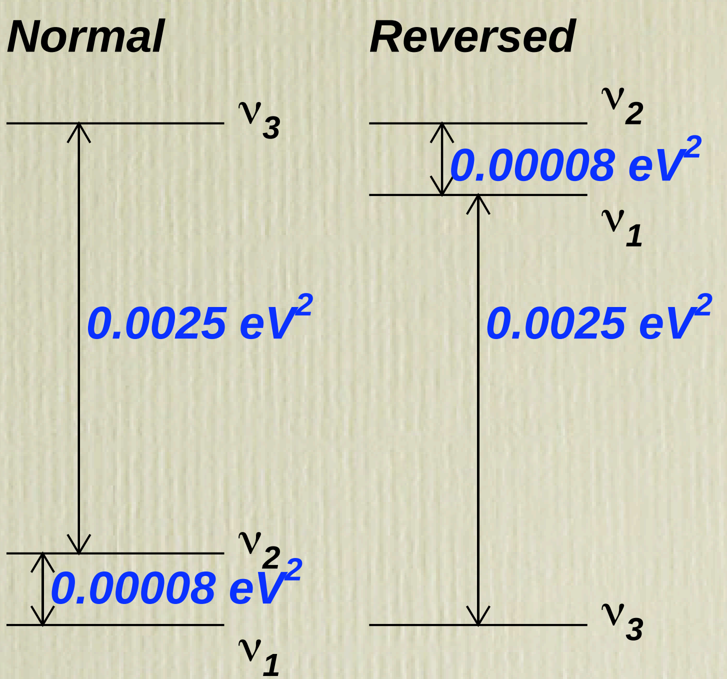
$$
\times \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}
$$

Majorana $\cancel{CP}$ phases

$\theta_{12} \approx \theta_{sol} \approx 34°$, $\theta_{23} \approx \theta_{atm} \approx 37\text{-}53°$, $\theta_{13} \lesssim 10°$

δ would lead to $P(\bar{\nu}_\alpha \to \bar{\nu}_\beta) \neq P(\nu_\alpha \to \nu_\beta)$. $\cancel{CP}$

mass-squares



Difference in mass squares: $(m_2^2 - m_1^2)$

Oscillation nodes at $\pi/2, 3\pi/2, 5\pi/2, \ldots$ $(\pi/2)$: $\Delta m^2 = 0.0025 eV^2$,
$E = 1GeV$, $L = 494km$. Solar : L~15000km

$\nu_\mu \to \nu_e$ with matter effect

Approximate formula (M. Freund)

matter effect ~E

~7500 km
no CPV.
magic bln

$$P(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23} \frac{\sin^2 2\theta_{13}}{(\hat{A}-1)^2} \sin^2((\hat{A}-1)\Delta)$$
$$+\alpha \frac{8J_{CP}}{\hat{A}(1-\hat{A})} \sin(\Delta)\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta)$$
$$+\alpha \frac{8I_{CP}}{\hat{A}(1-\hat{A})} \cos(\Delta)\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta)$$
$$+\alpha^2 \frac{\cos^2\theta_{23}\sin^2 2\theta_{12}}{\hat{A}^2} \sin^2(\hat{A}\Delta)$$

CPV term
approximate
dependence
~L/E

solar term

linear dep.

$$J_{CP} = 1/8 \sin\delta_{CP} \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23}$$

$$I_{CP} = 1/8 \cos\delta_{CP} \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23}$$

$$\alpha = \Delta m^2_{21}/\Delta m^2_{31},\ \Delta = \Delta m^2_{31} L/4E$$

$\hat{A} = 2VE/\Delta m^2_{31} \approx (E_\nu/GeV)/11$ For Earth's crust.

Science to be addressed with very large detectors and the beam

- Neutrino Oscillations.
  - ★ What is the size of last mixing angle, θ_{13} ?
  - ★What is the ordering of Neutrino masses?
  - ★Do Neutrinos violate the CP symmetry?

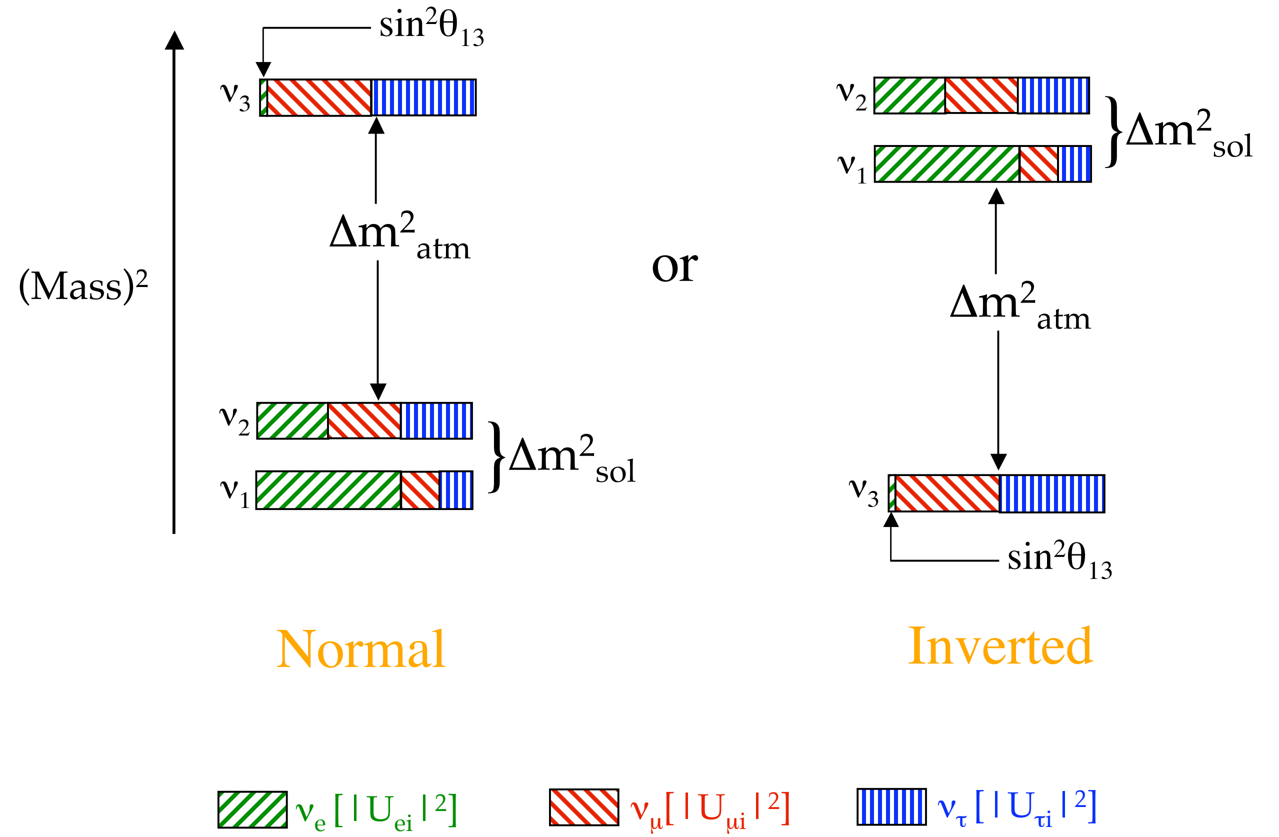
Importance θ_{13}

- There is little guidance on the size of θ_{13} but a small value is mathematically highly unlikely given the largeness of other mixing angles. A result such as could be a clue to some new symmetry.

$$\sin^2 2\theta_{13} < 0.01$$

Mass ordering

The spectrum, showing its approximate flavor content, is



- If found to be inverted, direct link to the GUT scale.
- If inverted and Majorana then double beta decay at 10-20meV

Neutrino CP violation

- Convergence of many profound theoretical ideas and observations:
    - ★ The see-saw mechanism
    - ★ Majorana nature of neutrinos
    - ★ Leptogenesis <=> Baryogenesis

Other Science

- Nucleon decay
- Neutrino astrophysics

Nucleon decay

$$Rate = a^2 \times m_N^5/M_G^4 \sim (10^{35} - 10^{36} years)^{-1}$$

$$M_G = 10^{16} GeV$$

- Almost accessible with next generation experiments ? May be ...
- Broad guidance: leading modes are
  - ★ nonsupersymmetric: $p \to e^+\pi^0$; current limit 8×10^{33} yrs (SuperK)
  - ★ supersymmetric: $p \to \bar{\nu}K^+$; current limit 2×10^{33} yrs (SuperK)

Neutrino astrophysics

- Galactic supernova: ~30000$\bar{\nu}_e$events/100kT of water with many types of events. ~few 1000 ν_e events in liquid argon,
- Diffuse (relic) supernova from z~1.0: 20-30 events above 10 MeV. Positive indication could be extra-ordinary.
- Solar neutrinos: day-night effect. Could collect 100000 events, need to measure 1-2% asymmetry.

Joint FNAL/BNL study

- Start Apr-06 in anticipation of physics urgency and DUSEL.
- Study also informed the NuSAG committee of US DOE
- Chairs: Hugh Montgomery, Sally Dawson; Committee: F. Cervelli(INFN), M. Diwan(BNL), M. Goodman(ANL), B. Fleming(Yale), K. Heeger(LBL), T. Kajita (Tokyo), J. Klein(Texas), S. Parke(FNAL), R. Rameika(FNAL).
- Several small workshops and ~10 documents from ~30 people on sensitivity, backgrounds, beam alternatives, etc.
- Scope of work (http://nwg.phy.bnl.gov/fnal-bnl)
  - ★ Accelerator intensity
  - ★ Beamline feasibility (NuMI offaxis/ to DUSEL) and rates
  - ★ Detector feasibility/Prelim. Costs/Schedule/R&D plan
  - ★ Backgrounds/Sensitivity

Two approaches

No new beam, but restricted physics because of surface det.

- Off axis: Use existing NUMI beam. NOvA will be built ~10mrad offaxis for the first maximum. (100kT LAR) could be built at either 10 mrad or 40 mrad for second maximum. Detectors will be on the surface. Combine the results to extract th13, mass hierarchy, and CPV.

New beam, but detector capable of Nucleon Decay

- Wide band Low Energy: Couple the long baseline program to a new deep underground laboratory (DUSEL). Site a large detector (~300kT if water Cherenkov or 100kT LAR) at approximately 5000 mwe. Build a new wide beam with a spectrum shaped to be optimum (0.5-6 GeV). Use detector resolution to extract multiple nodes.

- Concerns: event rate, NC background, resolution, parameter sensitivity, total cost and timeliness.

Proton Intensity at FNAL

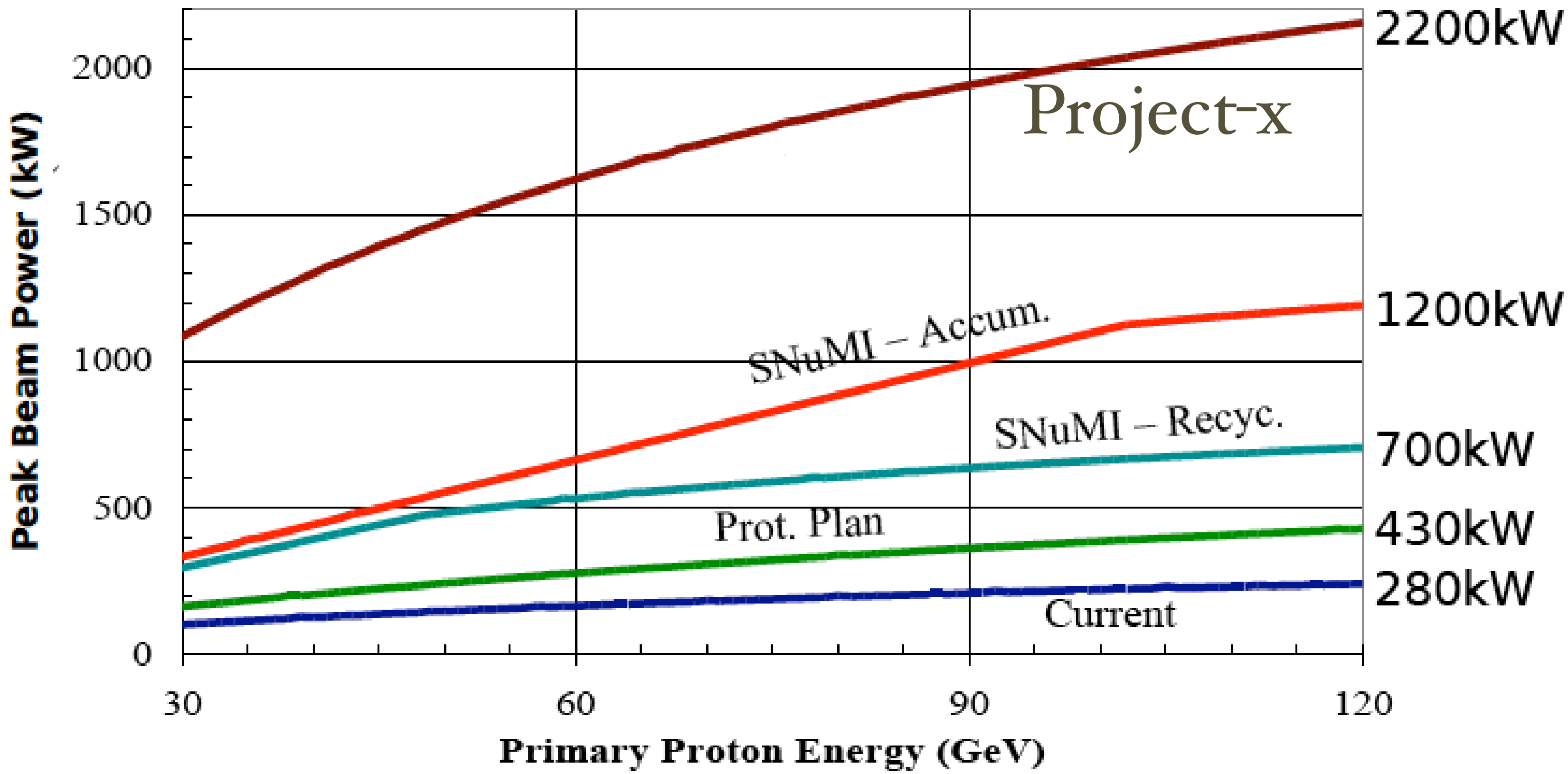
	Now	Proton Plan	NOvA *	SNuMI	Project X	
Batch Intensity (8 GeV)	4.4×10^{12}	4.3×10^{12}	4.1×10^{12}	4.5×10^{12}	5.6×10^{13}	protons/pulse
Rep Rate	7	9	12	13.5	5	Hz
Protons/hour	1.1×10^{17}	1.4×10^{17}	1.8×10^{17}	2.2×10^{17}	1.0×10^{18}	
Main Injector batches	7	11	12	18	3	
MI batches to pbar target	2	2	0	0	0	
MI Cycle Time	2.4	2.2	1.33	1.33	1.4	sec
MI Beam Power (120 GeV)	176	338	710	1169	2314	kW
8 GeV Beam Power (available)	18	17	16 *	0	206	kW
Injection energy into 1st synchrotron	400	400	400	400	8000	MeV

From: FNAL Steering group report.

Beam from FNAL

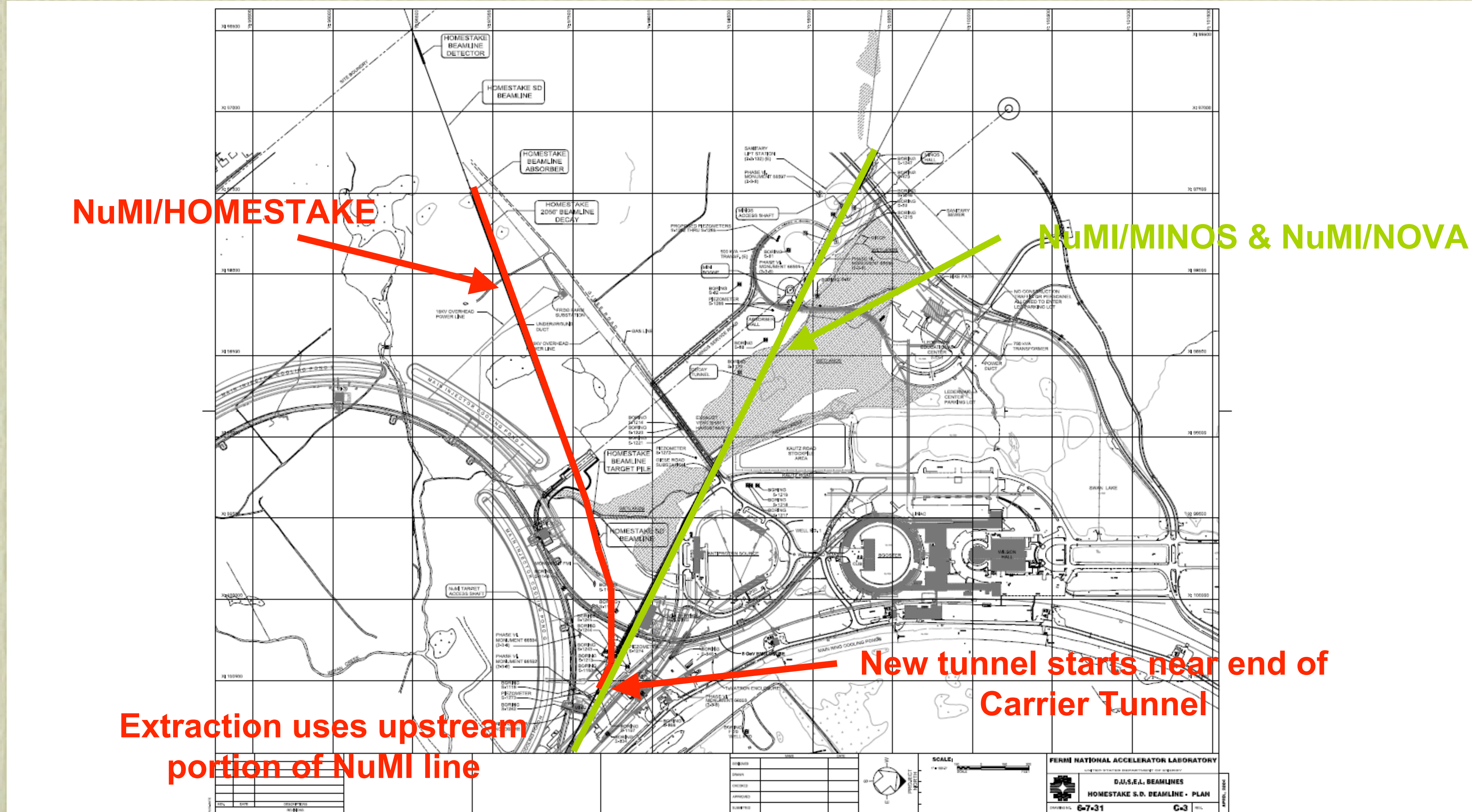
After Collider

Flexibility of proton energy:



1 MW* 10^7 sec = 5.2 10^{20} POT at 120 GeV

1MW*130 hrs/week*42 weeks = 10.2 10^{20}



Homestake/DUSEL Neutrino Beam

- •Use the present extraction out of Main Injector into NuMI
- •Second tunnel to transport protons west starts near lower Hobbit door in present line.
- • Radius of curvature same as MI for 120 GeV using conventional magnets.
- •New target station: R&D needed beyond 1 MW.

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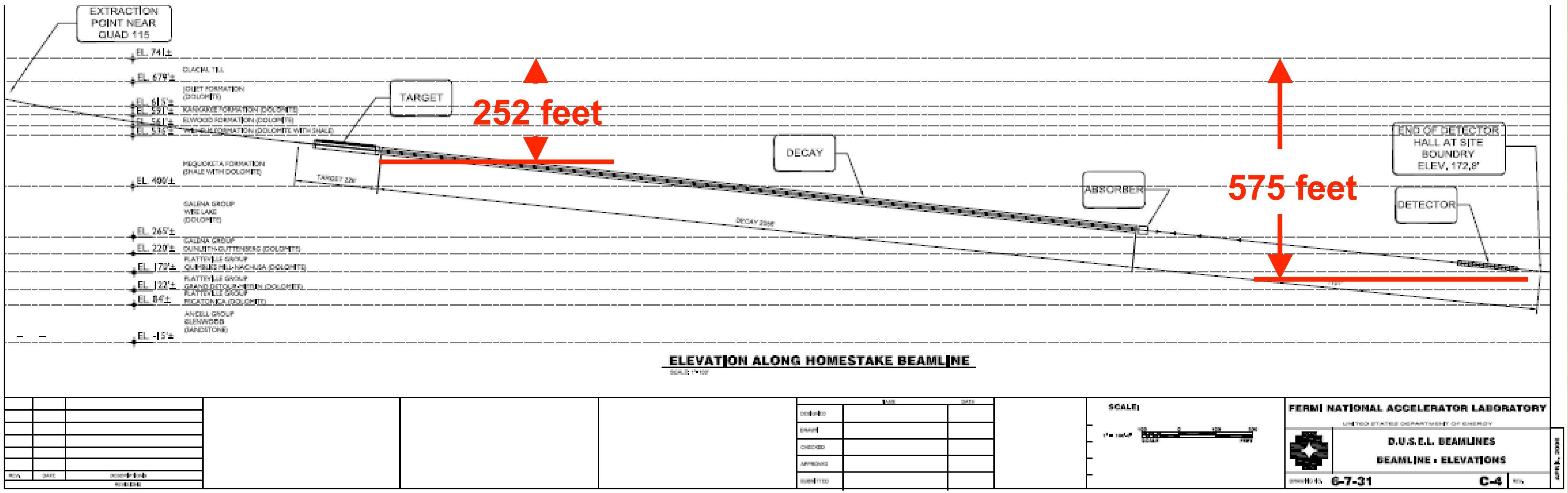
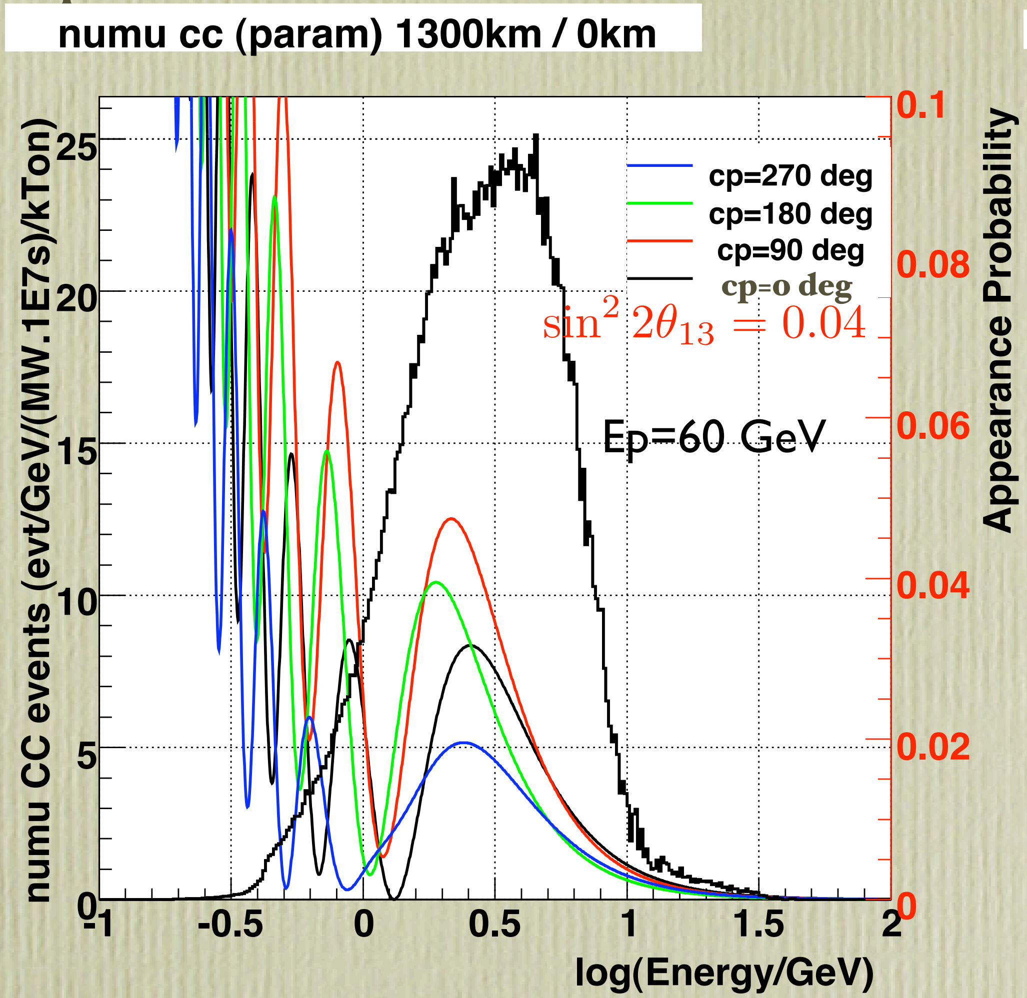
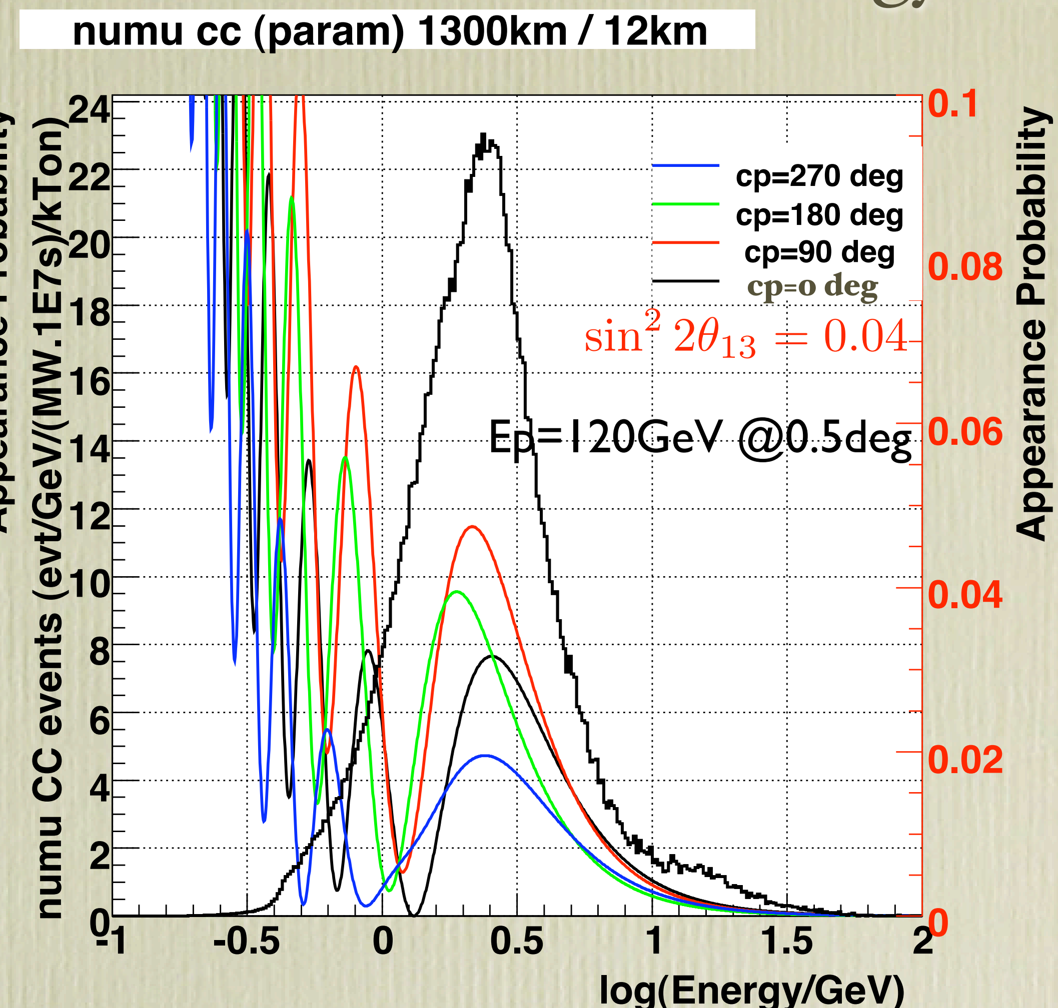
Elevation View



This elevation view of the Homestake Beamline (-5.84^{o}) is drawn to take the detector to the site boundary at Kirk Road. The maximum decay pipe length available in this configuration is about 627m (compare to NuMI at 675m). The detector hall (and shaft) is about 575 feet deep (compare to MINOS at about 336 feet). This is still in the Galena-Platteville but deep.

Spectra FNAL to DUSEL (WBLE: wide band low energy)





- 60 GeV at 0deg: CCrate: 14 per (kT*10^{20} POT)
- 120 GeV at 0.5deg:CCrate: 17 per(kT*10^{20} POT)

Work of M. Bishai and B.Viren using NuMI simulation tools

M.Diwan

$\nu_\mu \rightarrow \nu_e$ rate in 100kT*1MW*10^7 sec

$\Delta m^2_{21,31} = 8.6 \times 10^{-5}, 2.5 \times 10^{-3} eV^2$ $\sin^2 2\theta_{12,23} = 0.86, 1.0$ $\sin^2 2\theta_{13} = 0.02$

δ_{CP}

	$sgn(\Delta m^2_{31})$	0 deg	+90 deg	180 deg	-90 deg
NuMI-15mrad (810km)	+	76	36	69	108
NuMI-15mrad (810km)	-	46	21	52	77
WBLE (1300km)	+	87	48	95	134
WBLE (1300km)	-	39	19	51	72

$\sin^2 2\theta_{13}$	Events NuMI 12km 0CP, (+)	Frac. diff. wrt (-)	Frac. diff. wrt 90CP
0.02	76	0.25	0.36
0.1	336	0.23	0.15

Matter effect

CP effect

- Normalization: 1MW*100kT*10^7sec
- Significance for CP violation is different from matter effect. For large θ_{13} it is only weakly dependent on θ_{13}

Detector design considerations

- Need ~100kT efficient mass
- Signal ~50events/year
- 100kT→ 50m∅ × 50m h
- Cosmic rate in 10μs for 10^7 pulses.
- If detector on surface need rejection of ~10^8 for muons and ~10^4 for photons ➤ fully active fine grained detector.

Depth (mwe)	Intime cosmics/ year
0	5×10^7
1050	4230
2000	462
3000	77
4400	15 DUSEL

Detector technolgies

Water Cherenkov

- Known, successful technology with wide dynamic range (5 MeV-50GeV).
- Can perform both p-decay, astrophysical sources, and accelerator nus.
- R&D on large caverns already in progress. PMT R&D and costing in progress.
- Can be deployed deep scaled up: 50kT to fewX100kTon.
- MODEST DEVELOPMENT NEEDED FOR PROPOSAL.

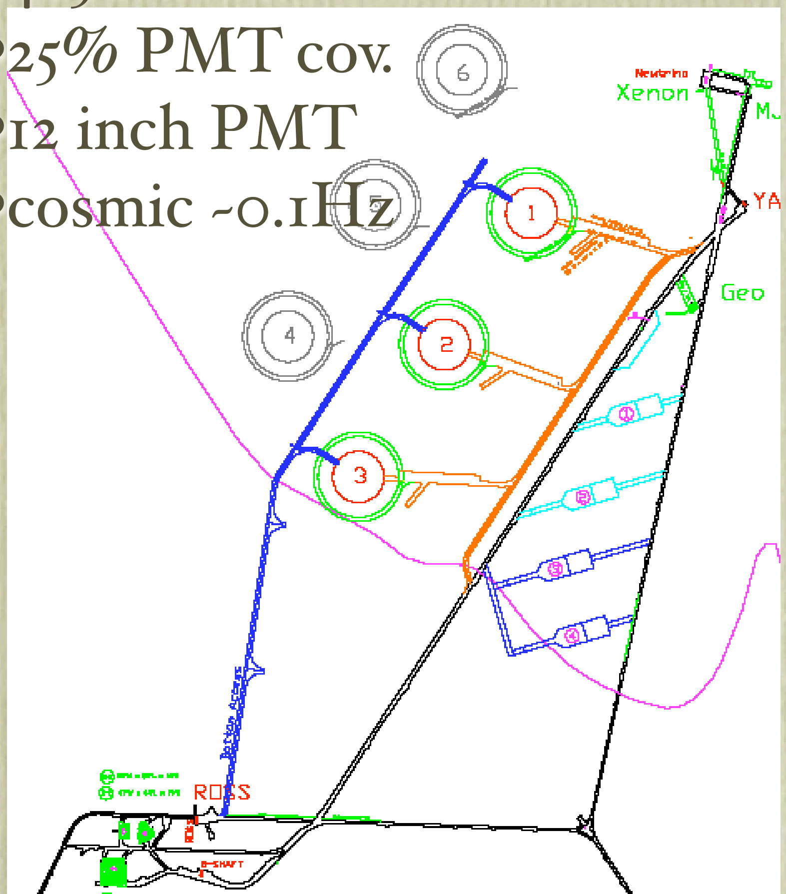
Liquid argon

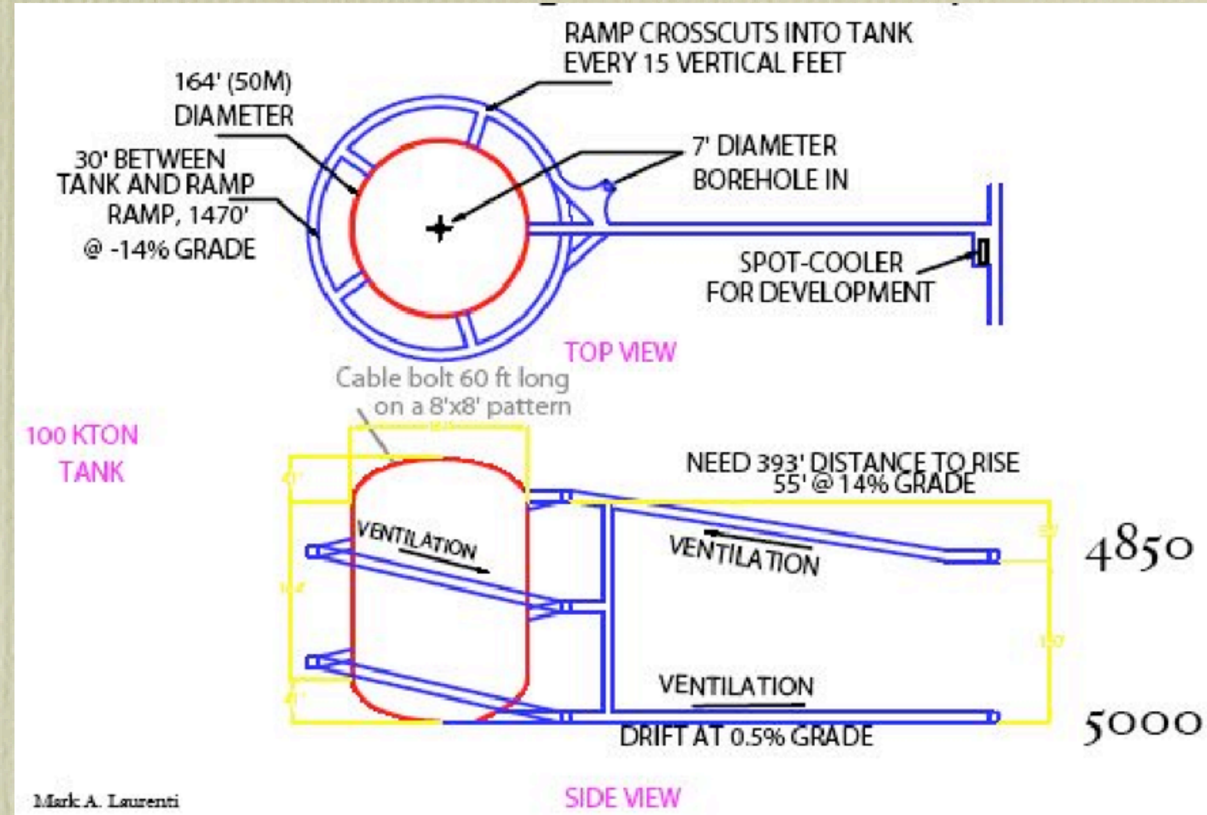
- Substantial R&D needed to scale current 0.3 kT (ICARUS) to 100kT.
- Solution needed deep deployment. Can proton decay physics or other non-accelerator physics be done near surface.
- Must demonstrate 10^8 rejection of cosmics as well as data rate capability.
- Aggressive successful R&D is needed to mount a proposal in 5 yrs.

Detector at Homestake

Modular Detector

- ~53m dia/h
- 100kT fiducial
- 4850 mwe
- 25% PMT cov.
- 12 inch PMT
- cosmic ~0.1Hz





Studies ~50m cavity stable in HS rock

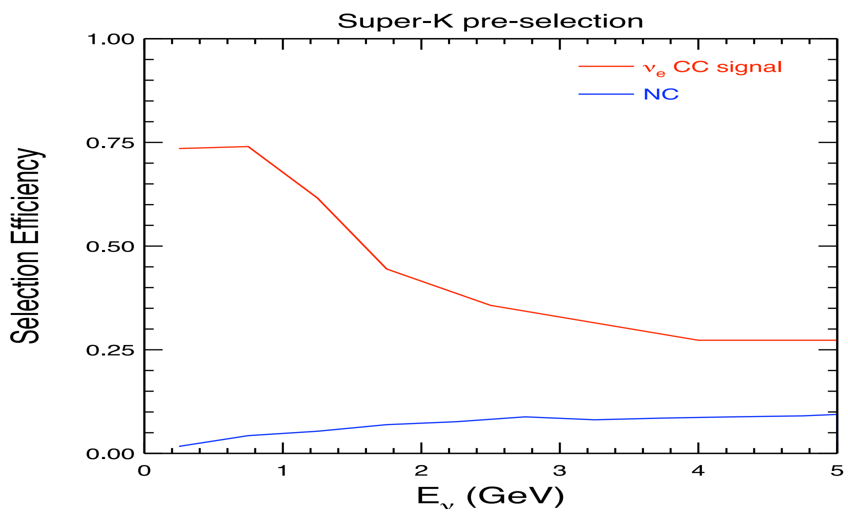
- ✓Initial detector 3 modules
- ✓Space can be planned for 10
- ✓ Cost estimate $115M/module
- ✓6 yrs construction to first 100kT
- ✓8 yrs to full 300 kT.

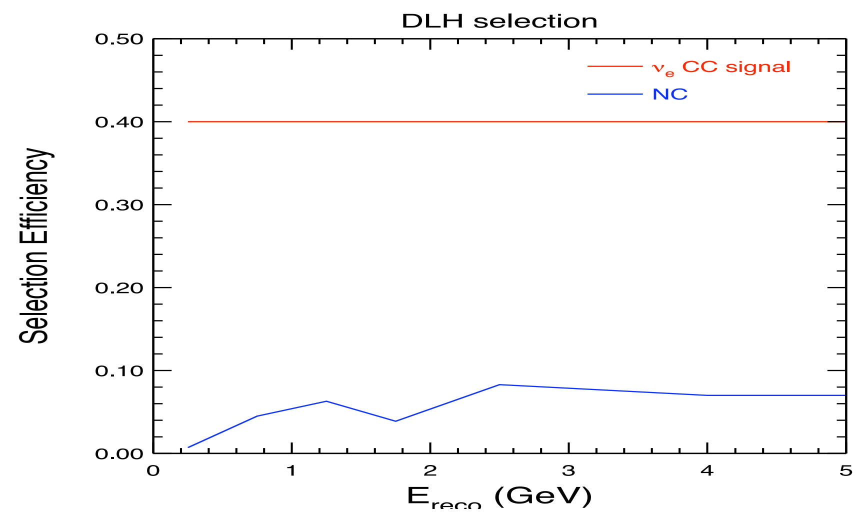
Fiducial vol depends on rock stability studies and PMT pressure rating.

Water Cerenkov Simulation

The ν_{atm} simulation of SuperKamiokande is used.

An π^0 reconstruction algorithim called "Pattern Of Light Fit" is used as input to a likelihood (DLH) analysis to reconstruct $\pi^0 \rightarrow \gamma\gamma$ by looking for the 2nd ring. **Independent studies by Chiaki Yanagisawa for FNAL-DUSEL WBB and Fanny Dufour for T2KK produce similar efficiency for signal and background.**





For total eff. and rej. multiply these plots together

Standard Super-K pre-selection efficiencies **DLH selection efficiencies (Chiaki Y.)**

WCe. energy dependent efficiencies and smearing implemented in GLoBeS.

LARTPC

www-lartpc.fnal.gov

B. Fleming, D. Finley, S.Pordes, et al.

- The LAR group has shown an advantage of about a factor 4 over a water Cherenkov detector of equal mass due to better background rejection. There is no easy automated event analysis, however.
- A 50 m high/dia tank on surface has 500 kHz of rate. LARTPC could take data around beamtime, but still need rejection of 10^8 on muons and 10^3-10^4 on gammas. This needs further work.
- Aggressive R&D path is needed including argon purity, industrial tank technology, readout geometry and signal/noise. First step : 1 kT before cost and schedule could be properly evaluated. Current scaling law is \$2.7M+\$0.3M/kT + \$1M/kTon (for LAR).
- Lower bound on 100 kT cost ~\$200M ?
- For $p \rightarrow K^+ \nu$ decay mode depth might be needed simply for data rate, and most likely for background.
- Such a detector can be placed at either NuMI off-axis or DUSEL.

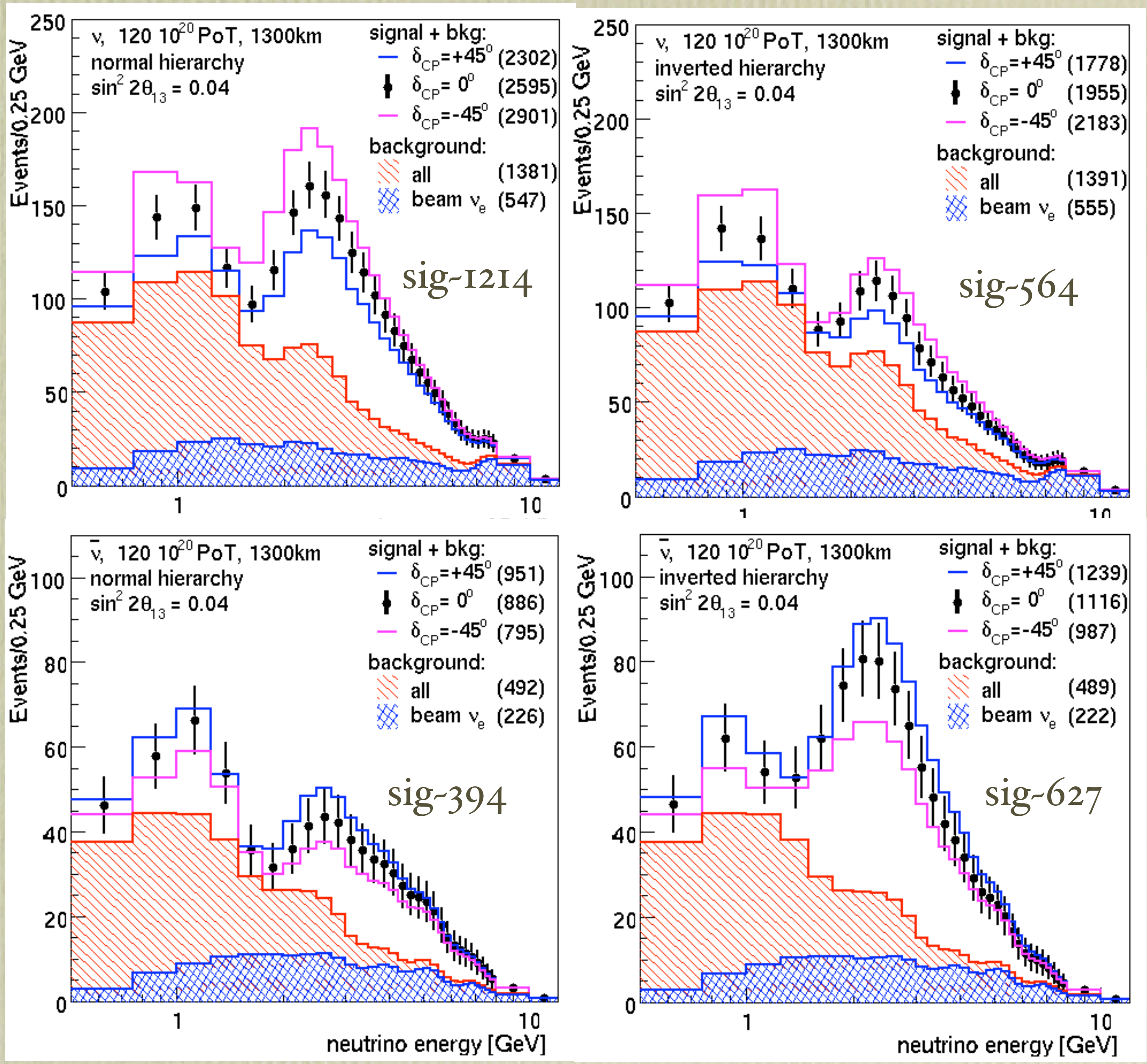
$\sin^2 2\theta_{13}$= 0.04, 300kT, 1300 km, ~2MW @ 60 GeV 3yrs neutrinos and 3yrs antineutrinos

$(-\ \delta_{cp} = -45°,\ -\ \delta_{cp} = +45°)$

Normal Reversed

Spectra with 300 kT detector and 2MW beam from FNAL

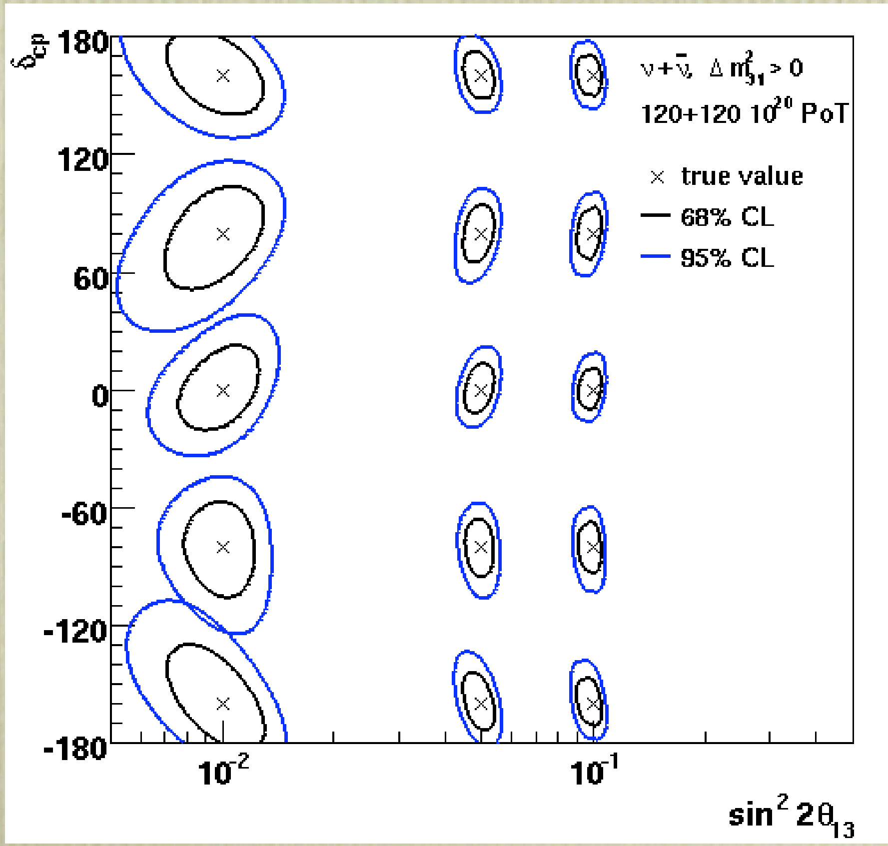
- Background issues examined by FNAL/BNL study.



Mark Dierckxsens(UChicago), Mary Bishai(BNL)

Technical issues

- Program should lead to measurement of 3-generation parameters without ambiguities. (recall: CP measurement is approximately independent of θ_{13}). Need large detector independent of θ_{13} value.
- An narrow band program cannot overcome ambiguities easily.

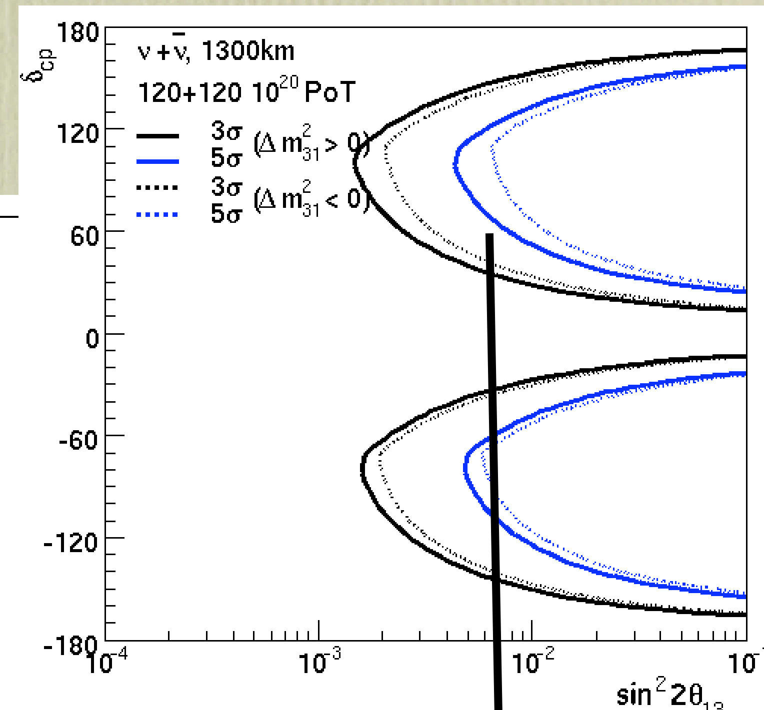


300 kT water Cherenkov detector @DUSEL
Measurement of CP phase and $\sin^2 2\theta_{13}$ at several points. All ambiguities and mass hierarchy are resolved.

Ultimate Reach

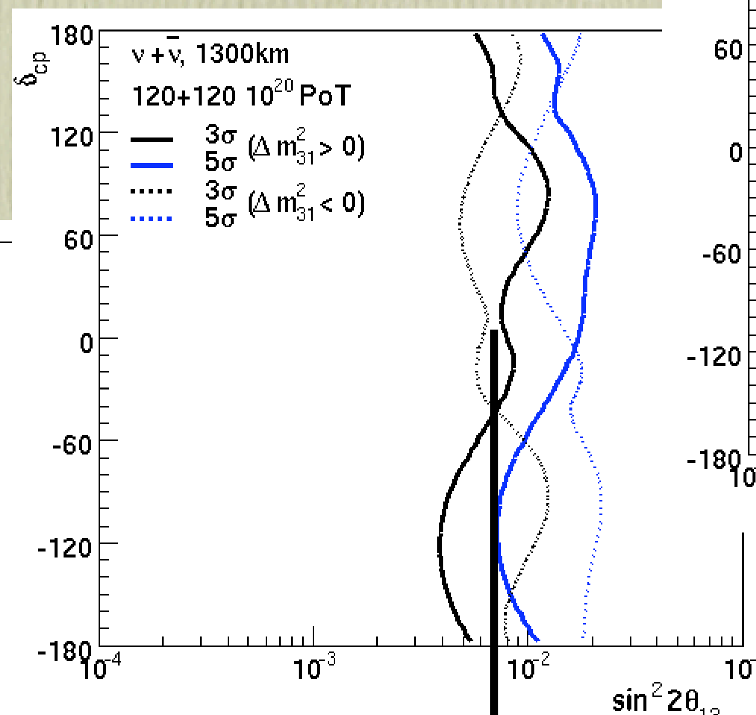
60 GeV, 2MW, 3+3 yrs, 300kT

CP Violation



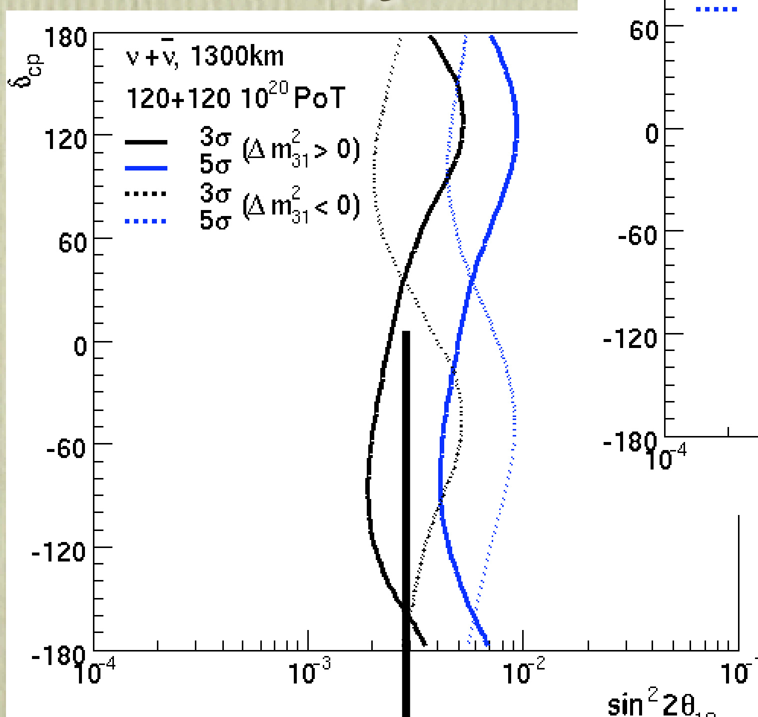
0.007

Mass ordering



0.007

θ_{13}



0.003

50% coverage at 3 sigma

stat+ 5%syst

Mark Dierckxsens(UChicago), Mary Bishai(BNL)

Intermediate proposal

- ~100 kT fiducial detector at Homestake with rock mechanics studies starting in fall of 2008. (Homestake Interim Lab. now exists, SuperK and SNO experience and success gives confidence in feasibility and performance.)
- New wide band beam from FNAL (pre-Project x)
- Focus on θ_{13}, and mass hierarchy.
- Get started on CP violation, p-decay, Supernovae.

$\sin^2 2\theta_{13}$= 0.04, 100kT, 1300 km, ~1 MW 60GeV 3yrs neutrinos and 3yrs antineutrinos

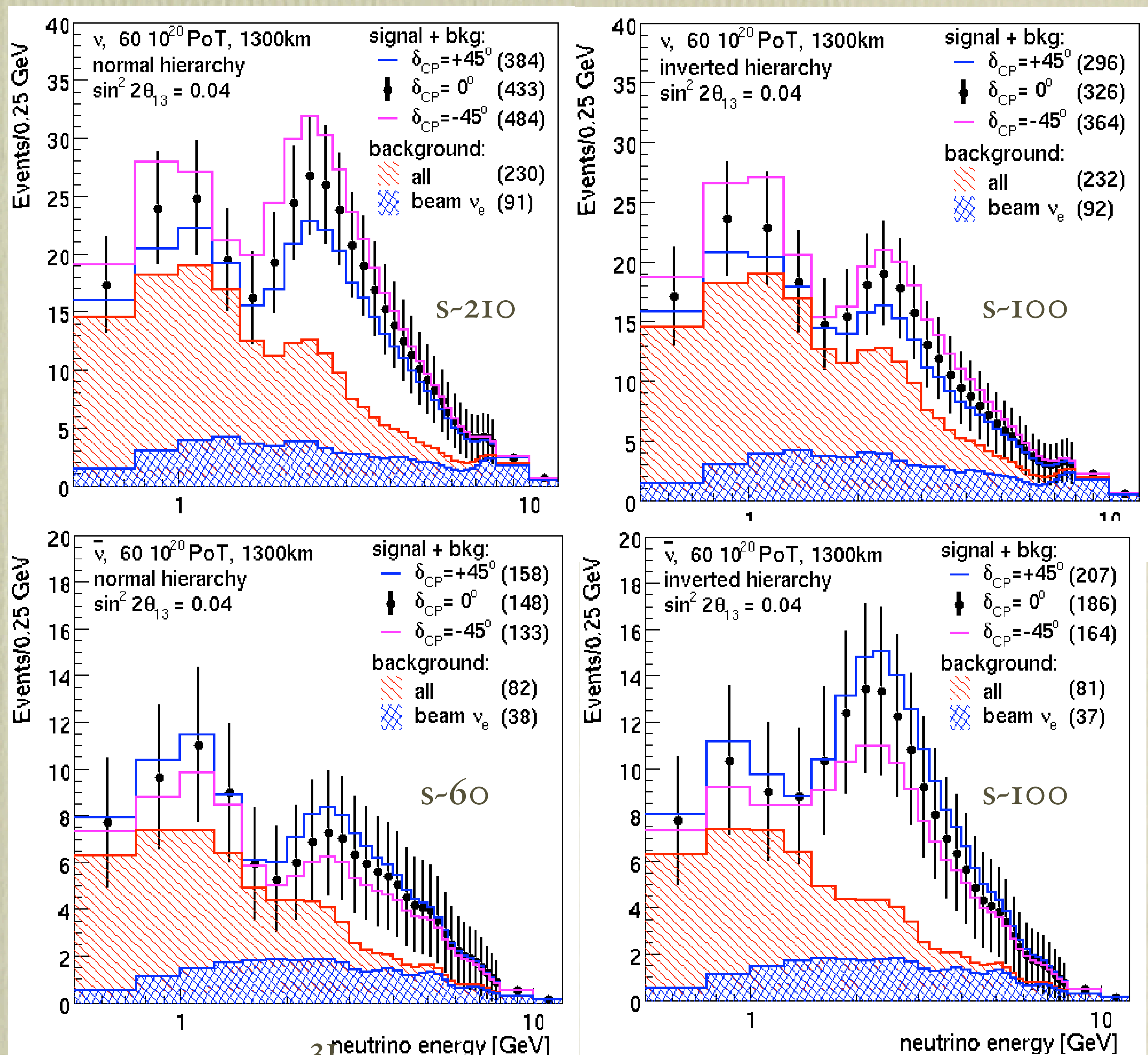
$(-\,\delta_{cp} = -45°,\ -\,\delta_{cp} = +45°)$

Normal Reversed

Spectra with 100 kT detector and 1 MW beam from FNAL

Total rate of events ~30k/yr

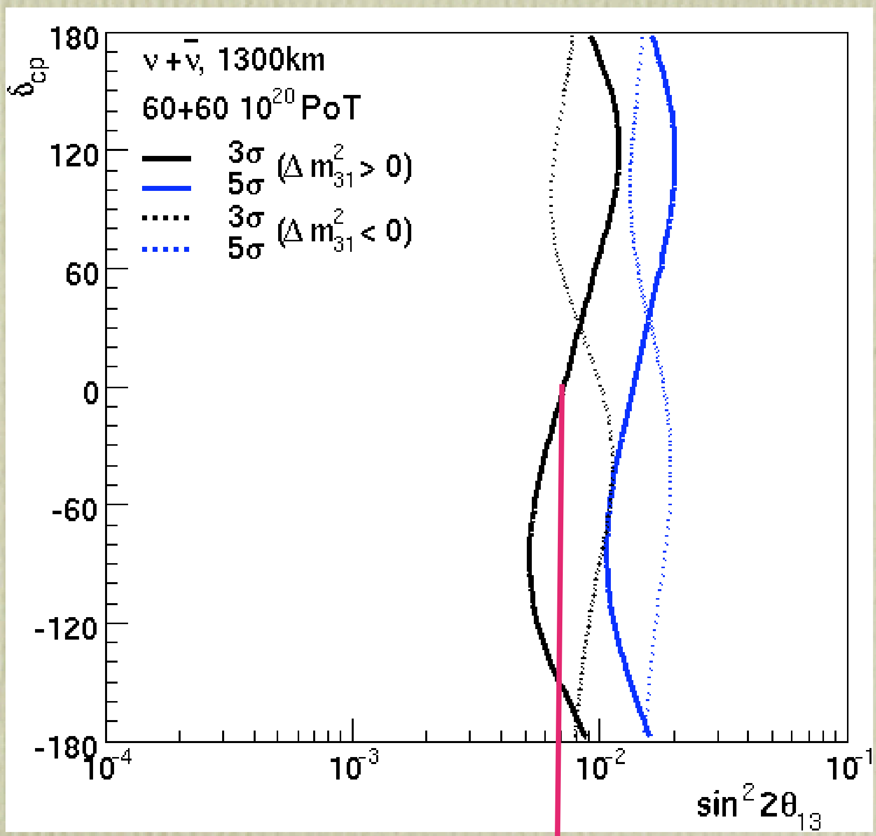
noosc/raw evts



Reach with 100 kT water Cherenkov

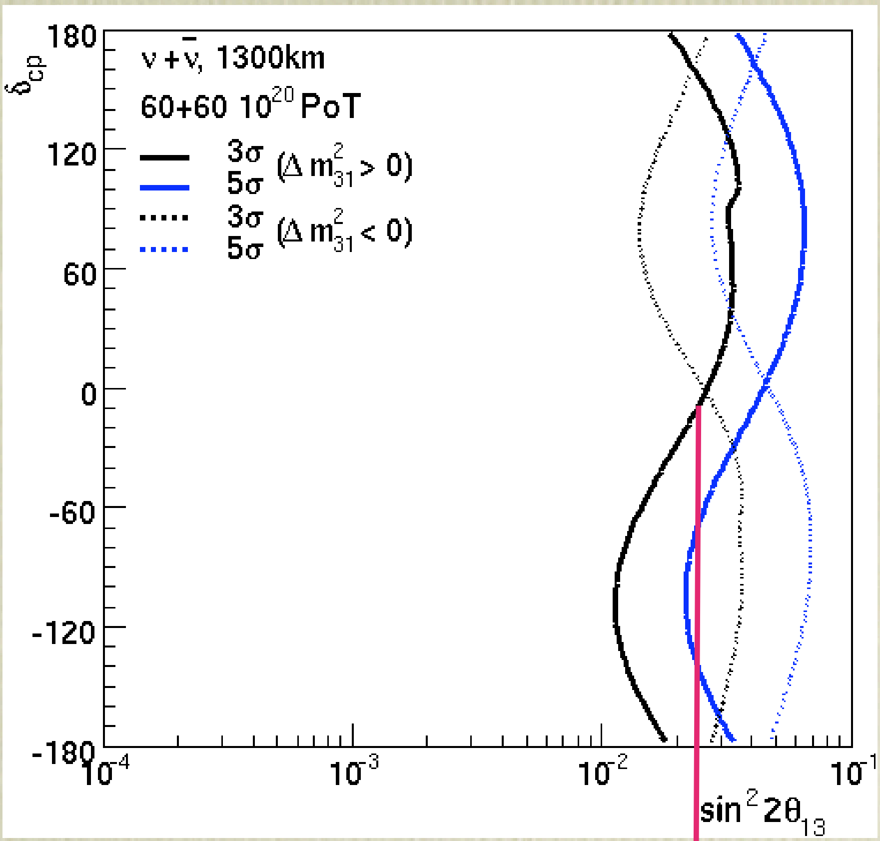
60 GeV, 1MW, 3+3 yrs, 100kT

θ_{13}



0.008

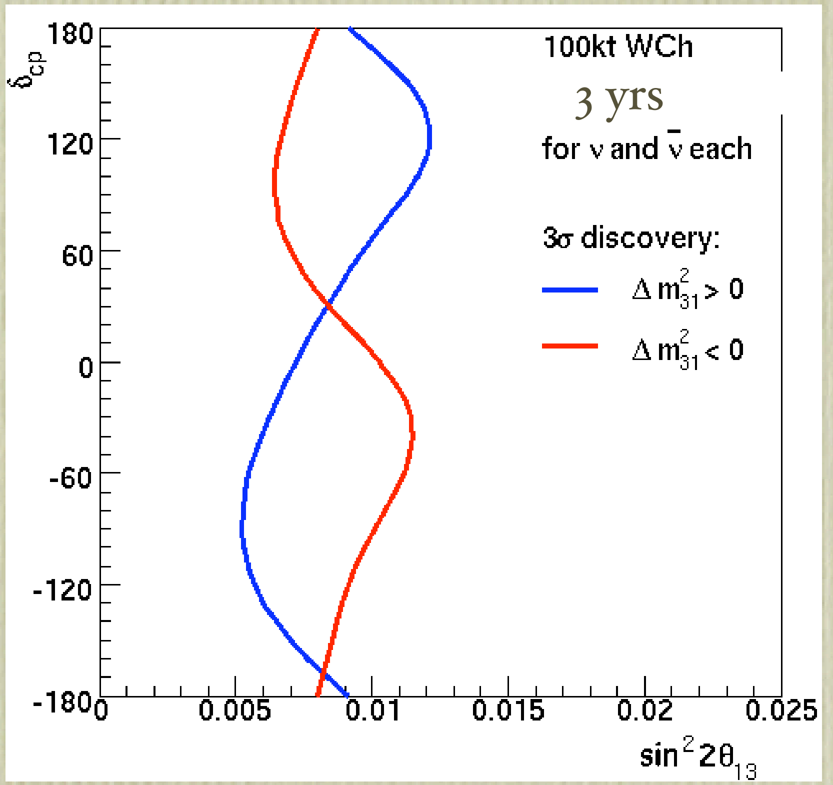
Mass ordering



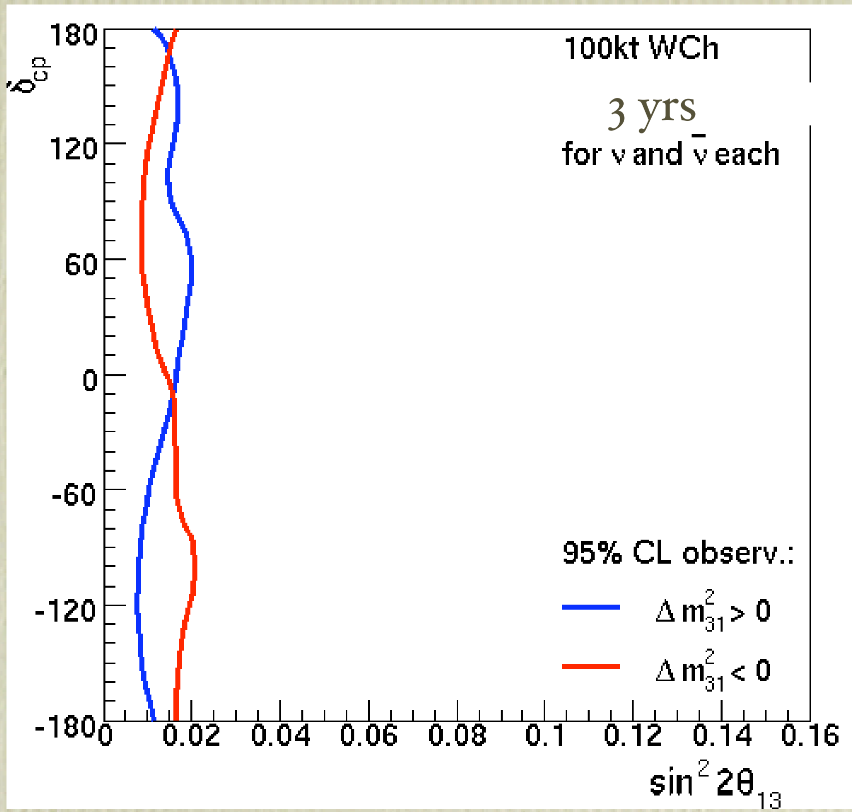
0.025

50% coverage at 3 sigma stat+5% syst

Same plots detail



θ13

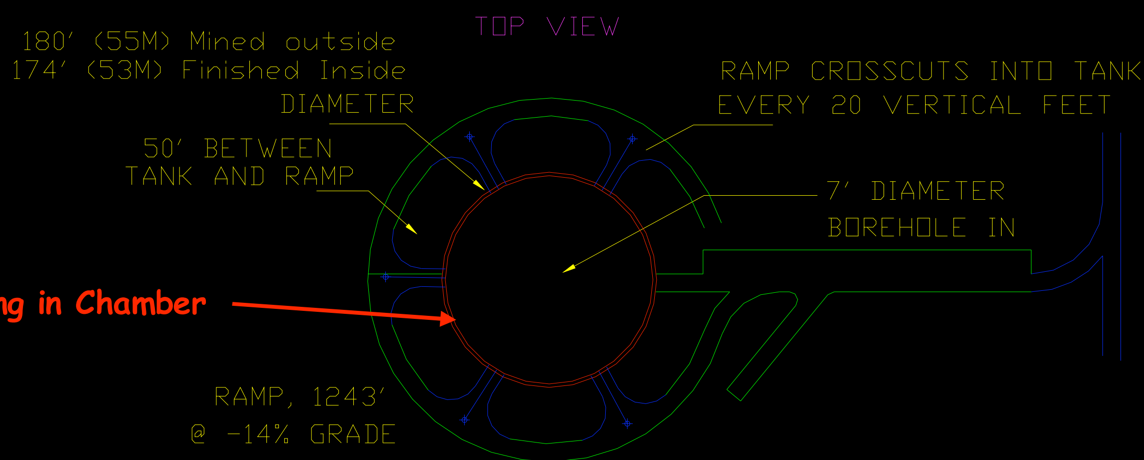


Mass ordering @ 2 sigma

- Same exposure in MW*10^7 sec as previous plot

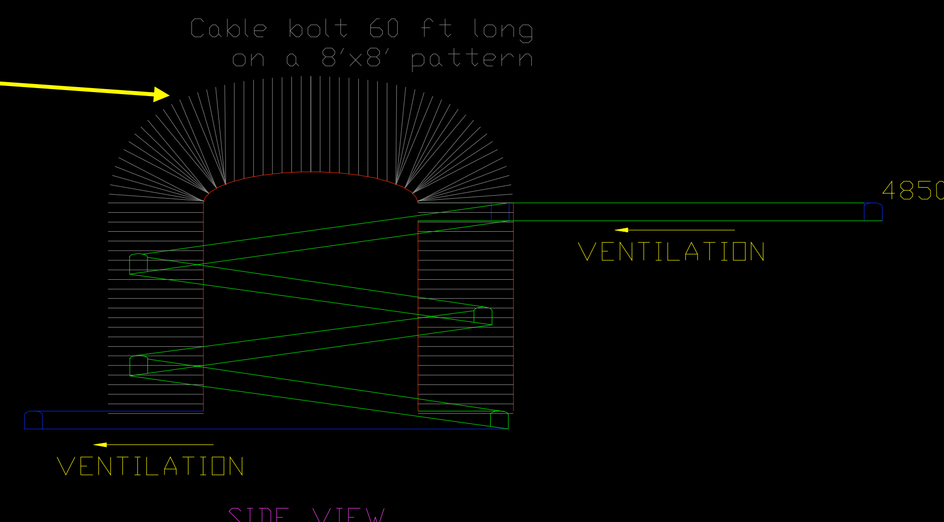
MEGATON MODULAR MULTI-PURPOSE NEUTRINO DETECTOR

✓ Chamber Design



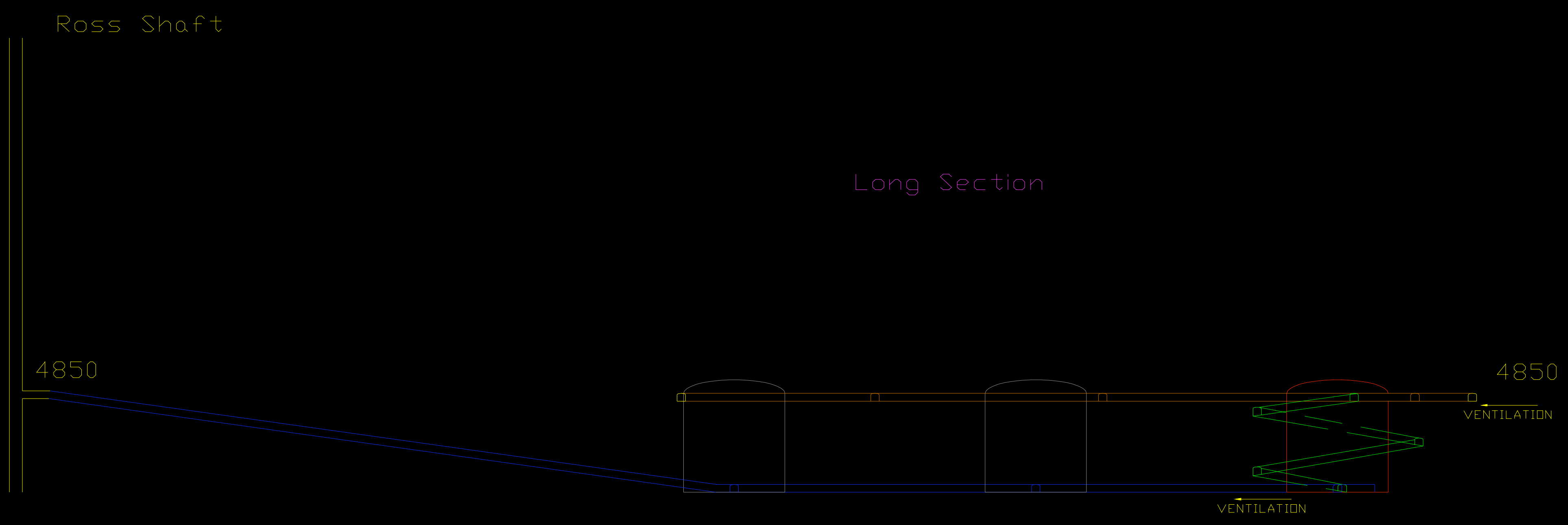
Controlled Blasting in Chamber

Could use Instrumented Cables for Engineering / Geotechnical Study



MEGATON MODULAR MULTI-PURPOSE NEUTRINO DETECTOR

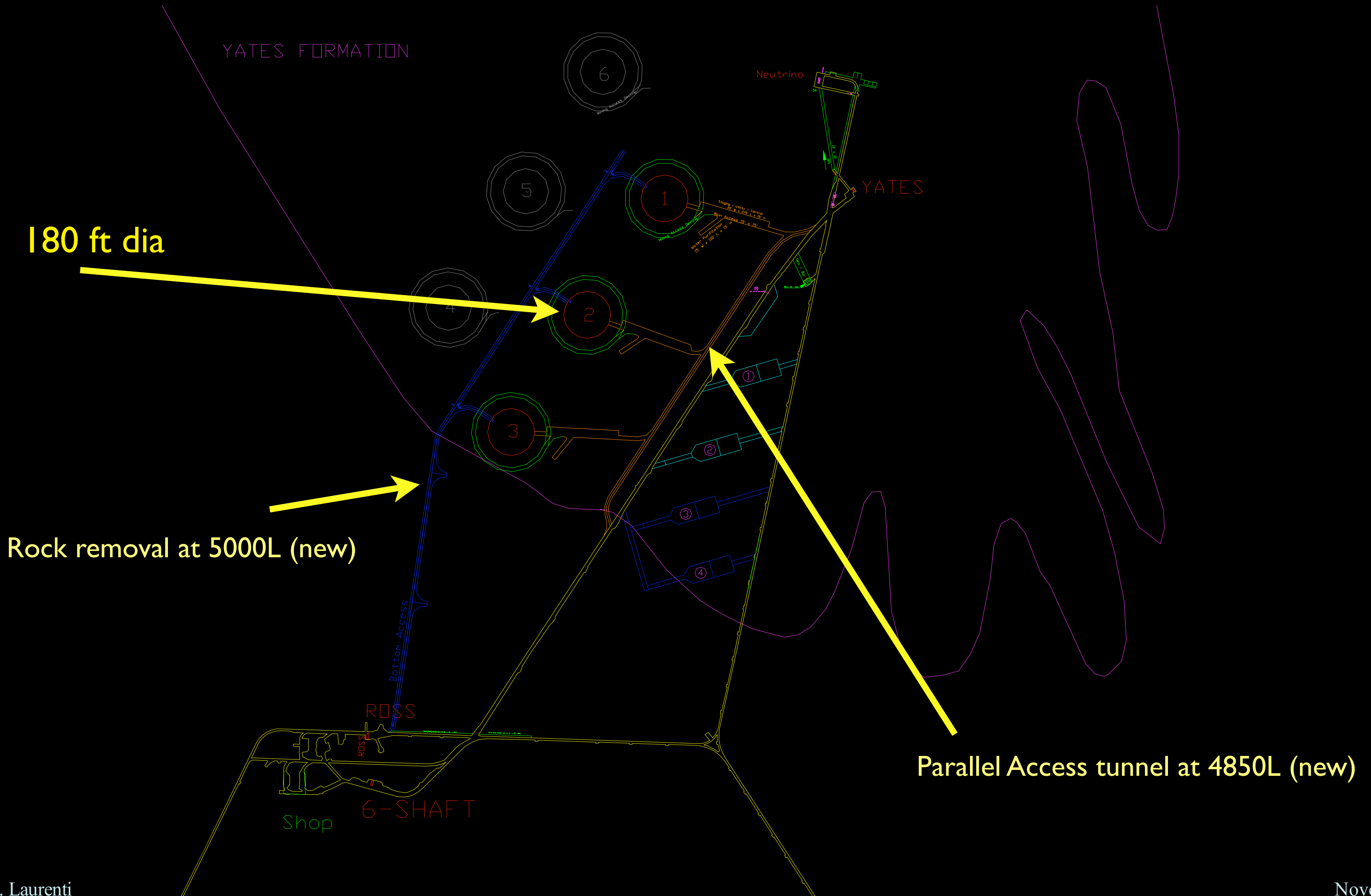
✓ Modular Configuration



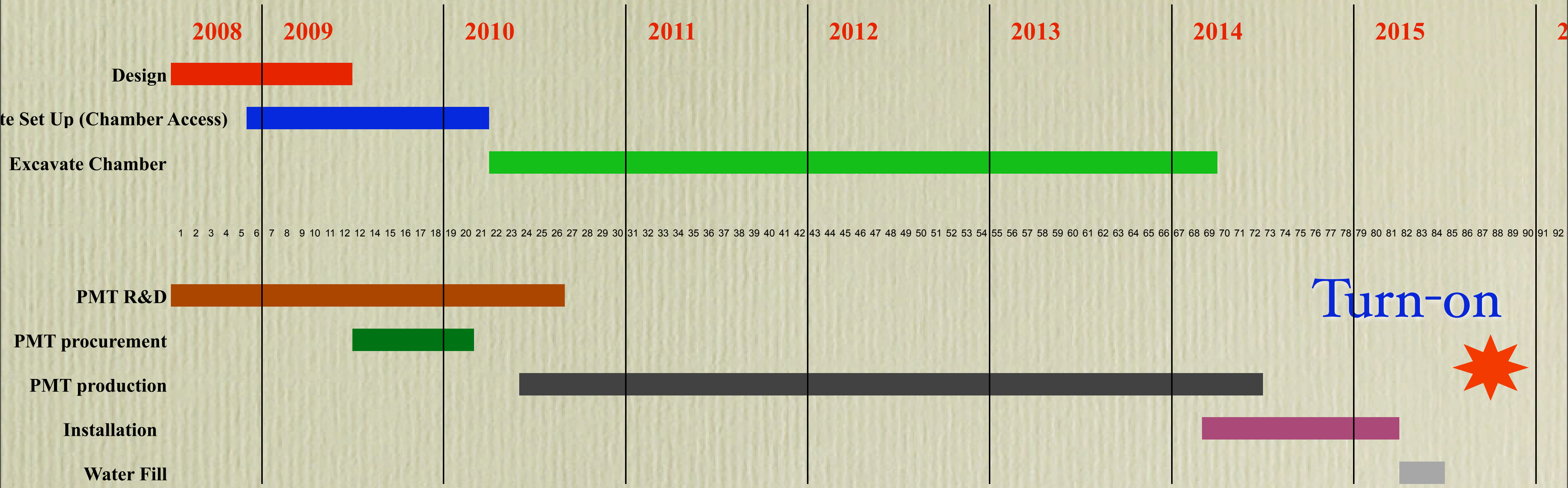
Megaton Modular Multi-Purpose Neutrino Detector

✓ **Modular Configuration**

muon rate/cavern~1/10 Hz



Technically limited schedule for a single 100 kT fiducial detector



Comments: Phototube production is slowed down to match construction of 1 module only.
Schedule is strictly technical. Does not account for review process. See KTLesko talk
PMT testing facility, water system procurement and installation, and other items are not shown here.

- Tube production is slowed to match excavation. Tube production is NOT the limiting factor.
- For simplicity, water system, PMT testing, electronics, etc. are not shown.
- For 300 kT the time need not be tripled.

One time costs over next 3 yrs

- 100kT estimate on next page does not include R&D and one time costs that are needed to establish the entire facility for the megaton-class detector.

Item	Cost	Source
Chamber design and coring	$0.76M	Laurenti
Access tunnels	$4.5M	Laurenti
Contingency	$2.6M	50% of above
Mining + other equip.	$10.0M	Laurenti
PMT+Elec. R&D	$4.0M	Prel. Eng.+Subcontracts
Water/materials R&D	$2.0M	Preliminary
Contingency (non-civil)	$3.2M	Equip. has quotes
Total	$27.1M	FY2007

Summary cost for 100kT(do not triple for 300kT)

Item	Cost	Source
Single Cavity construction	$28.1M*	Laurenti
contingency 30%	$8.4M	Preliminary Reviews
PMT(50000 chan)	$46.7M	Auger, NNN05, etc.
Electronics, cables	$10.65M	UPenn+SNO
Installation	$8.75M	Conceptual
Water, DAQ, testing, etc.	$11.4M	Quote, made for 300kT
Contingency(non-civil)	$25.0M	>30% for some items
Total	$139M	FY2007

* Cost and schedule reviewed by RESPEC, does not have rock disposal

Conclusion

- 100kT detector could be ready for physics by mid decade (~2015).
- Unique physics capability in the world. Excellent sensitivity for θ_{13} and mass ordering.
- Get started on much larger program for CP violation, Nucleon decay, and Supernova physics.
- Subsequent caverns could house different technology: better PMTs, Liquid Scintillator, Liquid Argon ...

Summary Of Chamber Excavation

	TOTAL	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7
Chamber (1)								
Cost / Chamber	**$ 28,059,334**							
	$ 28,059,334	**$ -**	**$ 6,980,751**	**$ 6,547,486**	**$ 6,815,666**	**$ 6,816,318**	**$ 899,113**	**$ -**
Top Cut (40 ft high)	**84,820 Tons**	-	84,820	-	-	-	-	-
Ramp Top to Bottom	**1,737 ft**	-	1,737	-	-	-	-	-
Bench Tons	**356,310 Tons**	-	-	127,170	101,970	127,170	-	-
Cable Bolt Feet	**275,840 ft**	-	41,760	64,480	69,360	85,240	15,000	-
Shot Crete	**1,800cuYd**	-	1,800	-	-	-	-	-
Concrete Panels	**2,376**	-	-	486	950	670	270	-
Bore Hole Feet	**174 ft**	-	-	174	-	-	-	-
Months	**49**	-	12	12	12	12	1	-
Labor	**$ 12,983,488**	$ -	$ 2,836,460	$ 3,290,928	$ 3,290,928	$ 3,290,928	$ 274,244	$ -
Equipment Operating	**$ 6,454,728**	$ -	$ 1,964,088	$ 1,601,208	$ 1,302,336	$ 1,491,840	$ 95,256	$ -
Supplies	**$ 8,534,118**	$ -	$ 2,180,203	$ 1,568,350	$ 2,222,402	$ 2,033,550	$ 529,613	$ -
Other	**$ 87,000**	$ -	$ -	$ 87,000	$ -	$ -	$ -	$ -

From Mark Laurenti

Excavation costs do not include
- General operations: mine, shaft, pumps, ventilation
- Overhead functions: office, property maintenance, water consumption, power.
- Mobilization/demobilization
- Waste handling
- EDIA
- Do not triple for 3 caverns.

Collaboration requesting funds from DUSEL R&D

One time costs

Summary Of Chamber Excavation

	TOTAL	Year 1	Year 2
Design (3 Chambers)			
	$ 761,600	$ 761,600	$ -
Months	7	7	-
Diamond Drilling ft	10,932 ft	10,932 ft	0
Diamond Drill Costs	$ 546,600	$ 546,600	$ -
Geotechnical Over site	$ 90,000	$ 90,000	$ -
Geotechnical Modeling & Recommendations	$ 125,000	$ 125,000	$ -
Site Set Up (6 Chamber Access)			
	$ 4,514,164	$ 3,958,652	$ 555,511
Drift Footage	4,667 ft	4,459 ft	208 ft
Months	8	7	1
Labor	$ 2,153,632	$ 1,879,388	$ 274,244
Equipment Operating	$ 1,143,072	$ 952,560	$ 190,512
Supplies	$ 1,217,460	$ 1,126,704	$ 90,755
Other	$ -	$ -	$ -

From Mark Laurenti